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Abstract

KAStrion was a project entitled "Current and vibration analysis for preventive and predictive condition-based maintenance in wind farms". It was fund by the KIC InnoEnergy from 2012 to 2014. The aim of this paper is to sum up and highlight the main results of the project. KAStrion goals were to maximize the production time of wind turbine farms by delivering a complete solution build upon a stand-alone analysis system which delivers a continuous on-site pre-diagnostic of the machine based on a multi-modal spectral monitoring technology. This embedded system located in the nacelle is connected to a tailored diagnostic center which delivers a periodic reporting on technical state of each machine of the farm. The strong innovation of KAStrion was to develop firstly a data-driven signal processing, referred to as AStrion, to automatically analyze, detect, classify all the spectral structures (harmonics and sidebands) of vibration signals, and secondly an original approach, referred to as SMESA, to process polyphase electrical signals. Contrary to existing systems, the coupling with the system kinematics is done after the analysis. KAStrion system has been tested on a specific test bench designed as a wind turbine at a smaller scale with load units on the main bearing, the planetary gear box and the output bearing in order to generate defects within an endurance test program. When compared with standard condition monitoring features, KAStrion shows its ability to characterize the start and the stage of the fault without the need of a historical data base. KAStrion system is also continuously tested on 2 two wind turbines in Arfons windfarm in France.

1. Introduction

Monitoring a dynamic system is an essential task for an optimal operating mode of the system but also for its safety and its cost-effectiveness. Many condition monitoring systems have been developed for this goal. Their efficiency depends on both the acquisition part and the processing one. First the choice of the quantities to be measured are essential wheareas the relevance of the processing which outputs health indicators of the monitored sytem should result in an early and reliable detection of potential failures of the components of the system.

This paper adresses this issue in presenting a synopsis of the main results of an European project entitled KAStrion which ended in December 2014. The basic idea of the project was to propose a new concept of monitoring a system. Most of existing systems are system-driven and provide indicators in line with the system kinematics. Moreover the data processing is set according to general knowledge and specifically for each system. In KAStrion, we have developed a complete and generic system which is fully data-driven and does not need any *a priori* knowledge on the measured data. Another strong point was also to input multi-modal data, vibration signals as well as electrical signals such as currents and voltages. The last being multidimensional we have proposed specific algorithms which simultaneously take into account the three phases in order to propose relevant and efficient indicators. And finally, from an original list of health indicators computed fully automatically, the last basic idea of the proposed concept is an automatic characterization of the trend of these indicators without referring to a database or historical data. This last step is crucial for avoiding the choice of critical thresholds in order to raise alarms.

In KAStrion project, this new concept is validated on onshore wind turbines. However, the concept can be used in any complex systems. Another application domain in manufacturing industry is currently the objective of a second European project entitled SUPREME where the concept is applied to the maintenance of a coated paper mill (18).

KAStrion project is born from the meeting of a set of partners, who join in order to gather their skills and expertise to support the conception and realization of a whole condition monitoring solution. From academic to wind farm day to day operational management, through signal processing and mechanics skills, software development and business activities, KAStrion was well setup to deliver a breakthrough innovative technology.

The main objective based on the new concept described above was to maximize the production time of wind turbine farms by delivering a complete condition monitoring solution to be installed in a wind turbine nacelle. Indeed, the last technological challenge was to embed all the processing in the nacelle close to the sensors.

This paper will only give an overview of the proposed approach. Further information for each of the following sections can be found in the other papers being part of the same conference session (1, 2, 3, 4, 5). In Section 2, KAStrion context will be presented. Section 3 will position the project face to the state of the art. Section 4 will focus on the main differentiator face to existing approaches. Section 5 and 6 will present the context of validation on a specific test bench developed within the project and on site installation in Arfons windfarm in France.

2. KAStrion context

KAStrion project is the conception and development of a full condition monitoring system. In addition of the technological challenge, the motivation is also economical.

Due to the origins of failures as presented in Figure 1, external causes account for less than a quarter of the total number of failures(17). The most common failure cause in wind turbines is the defect of parts of the system and it accounts for more than a third of the total failures.

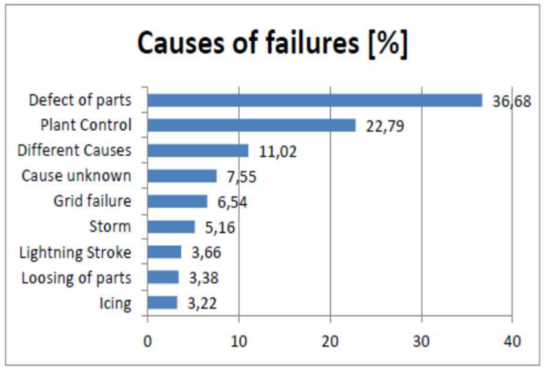

Figure 1. Causes of failures in wind turbines
[WMEP 2006 http://www.windmonitor.de]

In an in-depth analysis of the differents parts of a turbine, Figure 2 shows that the most damage-prone elements are not the more severe for the wind turbine owner. Contrariwise, the group gearbox, generator and main shaft represent only 13 % of the total failures but 50% of the wind turbine shut-downs induced by the large amount of time necessary to repair such components. Gearboxes and drive trains are the most critical mechanical components as they generate the most amount of downtime per failure.The rotor has both a high failure rate and a high amount of downtime per failure. Moreover, its failure rate tends to increase with the power generated by the turbine.

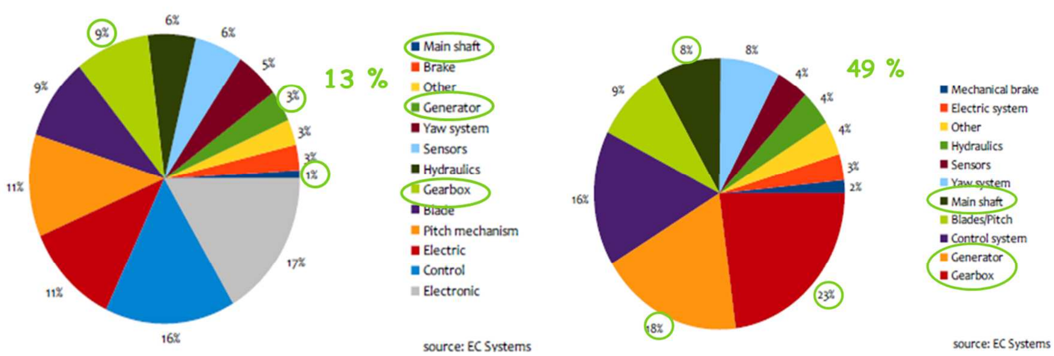

Figure 2. Distribution of the number of failures and percentage of down-time for different components [EC-System 2011]

Going further, Figure 2 also shows high failures due to electrical components even if they do not usually generate a large amount of downtimes per failure. These components show a wide range of failure modes due to internal as well as external causes. The convertor and control system are the most critical ones. In offshore operating conditions, electrical components are expected to have an even higher failure rate than onshore, as they tend to be more sensitive to external and environmental parameters.

Given that they do the connection between the mechanical and the electrical components, electrical generators might be regarded as a key element which have average failure rate and average amount of downtime per failure.

From a maintenance point of view, the major cause of the mechanical failures is the wear and so forth a preventive maintenance strategy is clearly possible for mechanical components. A wear failure usually generates a gradual degradation, which is predictable with efficient condition monitoring systems. The issue is much more complex for electrical components. Indeed, causes of failures are in that case multiple and can be equally progressive, such as wear, or instantaneous and unpredictable, such as grid outage or lightning. In that case, a monitoring system with efficient fault detection and diagnosis methods dedicated to electrical components is still very interesting, since it allows using efficient corrective maintenance strategies.

KAStrion condition monitoring system will monitor both mechanical and electrical components in order to allow the definition of an appropriate preventive maintenance strategy, which in turn can significantly decrease the percentage of failures due to parts of the system, and so the economic losses.

KAStrion project has been funded by the KIC InnoEnergy from 2012-2014. The consortium is composed of 7 partners commited for their skills

1. Grenoble Institute of Technology, G-INP, Grenoble, France - the manager of the project, through GIPSA-lab skills in signal processing, electrical engineering, condition monitoring and algorithm development;
2. Toulouse Institute of Technology, INPT, Toulouse, France - through IRIT lab skills in signal processing, fault diagnosis, bayesian technics;
3. The Technical Center for the Mechanical Industry – CETIM, Senlis, France – for its skills in mechanical test bench conception, machine knowledge, machine diagnosis and condition monitoring;
4. EC-Systems, Krakow, Poland - a PME renowned for the design of monitoring and diagnostic systems for wind power project;
5. VALEMO, Bordeaux, France - a PME as a end-user specialized in the operating follow-up and maintenance of renewable energy installations;
6. MECAL Wind Farm Services BV, Enschede, Netherlands - a PME as a end-user expert in wind turbine inspection and monitoring.
7. GRAVIT, Grenoble, France - an innovation structure having skills in technology positioning, market assessment, industrial property strategy and industry transfer.

3. Face to the state of the art

The literature on condition-based maintenance, diagnostic and prognostics is very rich, hundreds of papers are published every year and many patents are deposited. This section is just to sum up the current methodologies and to refer to some reviews as entry point and without exhaustivity[6, 7, 8]. This section aims at positioning KAStrion among existing methodologies without taking account of the management of maintenance in the company. This last point is also crucial but out of the scope of this paper. Likewise the analysis of oil, temperature and data from sensors as acoustic emission will not be considered.

All papers and existing systems agree on the same basic set of methods for the vibration analysis of roller bearings and gear wheels. In a nutshell:

1. Statistical algorithms applied on time signals and essentially on vibration data: the time amplitude density of vibration signal is normally distributed, if the damage of the fault starts to develop, this distribution deviates from the Gauss-shaped curve. This method gives an absolute measure of the state of a any bearing but does not point to the nature of the failure;
2. Time-domain analysis: estimation of characteristic features describing a time-signal and essentially showing variations of amplitude (crest value, peak-to-peak value) or statistics of the signal (mean value, root-mean-square value, skewness, kurtosis);
3. Frequency-domain analysis: the Fast Fourier Transform gives the opportunity to isolate and identify characteristic frequencies of the system, the order analysis is necessary for variable speed components.

Being less standard or somehow more complex to apply, we can mention the envelope analysis and side-band demodulation in order to highlight amplitude and frequency modulations generated at every revolution of a gear wheel by a failure on the gear, the cepstrum to identify harmonic families, high-order spectra able to deal with non-Gaussian signals, the spectral correlation to separate cyclostationary of order 1 (deterministic part) from the one of order 2 (random part) in order to differentiate gear from bearing faults and parametric model to fit to the measured data. Time-frequency analysis are more and more concerned in diagnostic approach. Time-scale approach gives the possibility to adapt the wavelet form according to the nature of the failure to detect. Synchronous average is a nice technic to reduce signal to noise ratio.

Condition monitoring of the electrical parts of wind turbines is more recent in the literature and less implemented in marketed CMS. With the use of sophisticated software, the monitoring of winding currents estimates asymmetries that state about the faults.

Patents in the domain deliver solutions essentially based on broadband spectrum analysis which are deficient for detecting incipient faults. Protected methods offer low performance in terms of computational power prohibiting the necessary embedded processing of sufficiently long time duration data for the fault detection of low-frequency components, for example the low-speed main shaft of a wind turbine. One solution assumes the unrealistic availability of sensors within the planetary gearbox structure. Others are characterized by the assumption of signal stationarity without checking this property. Finally some solutions apply a fleet-based diagnostic model based on trend patterns and data characteristics of all the systems. These solutions assume a high degree of similarities among the different systems of the fleet.

For the last step of decision-making, the alarms produced by existing condition monitoring systems are generated according to predefined level settings, regardless of the turbine operational state and of the measured data.

A review of 271 papers in 2006 (6) concluded inter alia that systems at that time were deficient in data collecting which has limited the use of advanced signal processing. The prescribed direction of research for the future was to develop systems with robust on-line data acquisition, efficient and fast on-line signal processing algorithms, robust fault detection and fault diagnostic approaches. Paper (6) ended its review as follows "*a future trend of CBM [Condition-based maintenance] research and developments would be the design of intelligent device which has the capability of continuously monitoring its own health using on-line data acquisition, on-line signal processing and on-line diagnostic tools*".

It can be said that in 2015 KAStrion fits well within this prediction.

As mentioned in the introduction, KAStrion is a project which brought several innovative solutions. KAStrion CMS system is embedded in the nacelle close to the sensors. It has the possibility to acquire signals in real time and to compute advanced signal processing in order to output and transfer characteric features of the state of the system and potential system failure alarms. The system is fully automatic and provides a continuous monitoring.

The data processing is preceded by a data validation in order to check the validity of the measure which could be affected by a sensor problem and also the stationarity property of the signal absolutely necessary for the following spectral analysis.

The proposed approach provides a multi-modality maintenance by processing both vibration and electrical signals (currents and voltages). KAStrion CMS includes a specific polyphase electrical analysis in order to provide efficient fault detection.

A strong innovative point of the approach is to analyse all the frequency bands of the measured data independently of the kinematics. KAStrion CMS is to be able to monitor any system and above all not to miss an unexpected evolution of the spectrum. It is the basis of a data-driven approach where the analysis is conducted from measured data only.

In a specific offline center, all the raw signals are easy to reach in a database and a user interface allows an interactive display of the features sent by KAStrion CMS. Furthermore this interface gives the possibility to see more detailed results or if necessary to analyse other raw signals.

4. KAStrion main differentiator: a disruptive signal processing

The aim of this section is to present the synopsis of the set of signal processing methods proposed in KAStrion project. As mentioned in the introduction the details of the different parts or modules can be found in the following papers of the structured session dedicated to this project[1, 2, 3, 4, 5].

KAStrion relies on two new approaches. One can be seen as a spectral analyzer and is referred to as AStrion developed by G-INP and INPT partners. It has the ability to process any signals whatever its physical origin might be. In KAStrion project, vibration signals, estimated modulation functions as well as electrical signals are provided to the inputs of AStrion. The other one is a specific tool for processing three-phase electrical signals, it is referred to as SMESA developed by G-INP partner. In KAStrion project, three-phase current signals as well as voltage signals are provided to the inputs of SMESA. This whole process applied in a continuous way confers to KAStrion CMS the ability of detecting faults within the whole frequency band of the measured signals and, above all, of characterizing the start and the stage of the faults.

4.1 AStrion

The processing apprehended in AStrion belongs to time, frequency and time-frequency domain. The core idea is to exploit the Fourier transform which is indeed a very well adapted tool for studying vibration and electrical signals. Applied on a long enough signal correctly sampled, the Fourier transform is able to provide an estimation of all the frequency content with a very high spectral resolution. As shown in Figure 3, AStrion is currently decomposed in 7 modules:

1. AStrion-A for Angular resampling: if a phase marker is available, the signal is resampled in angle in order to suppress nonstationarities due to small variations of speed. According to classical way of doing, outliers are detected and replaced with interpolated points.
2. AStrion-D for Data validation: KAStrion system includes some prelimary tests on the validity of sensors. AStrion-D adds tests for raising alarms if the data are saturated, *a posteriori* badly sampled or nonstatinary. In any case AStrion-D provides indicators about the signal periodicity and an estimated value of the global signal to noise ratio.
3. AStrion-I for peak Identification: This module provides the result of the spectral estimation of the data. The only drawback of a Fourier transform applied on long time duration signals is a high estimation variance. This issue is solved with the help of frequency detectors and classifiers based on the statistical properties of the used spectral estimator. Setting from AStrion-D outputs, AStrion-I outputs a list of so-called identity cards, one for each frequency pattern of interest according to the spectral estimation characteritics, and provides of a list of attributes describing the associated pattern.
4. AStrion-H for Harmonic series and side-band detection: Identity cards are grouped in quantities of great interest in a CMS context.
5. AStrion-K for Kinematics: If available, kinematics of the analysed system is used in order to label the identity cards with system components. This stage is optional given that the process is driven by the measured data and not by the *a priori* information.

6. AStrion-M for demodulation: All detected side-bands output from AStrion-H are demodulated with an automatic filter setting from the attributes of the side-bands themselves. This setting solves a critical and often overlooked issue in the process of demodulation. AStrion-M adds to the identity cards a list of indicators associated to these demodulations.
7. AStrion-S for Surveillance: The conception and development of this module are still in progress. AStrion-S aims at tracking all the indicators in time in order to output abnormal trends and then relevant alarms of failures. An important feature of AStrion is the setting of alarms from the currently analysed data and not from historical one and without predefined thresholds. It is the core of this data-driven system.

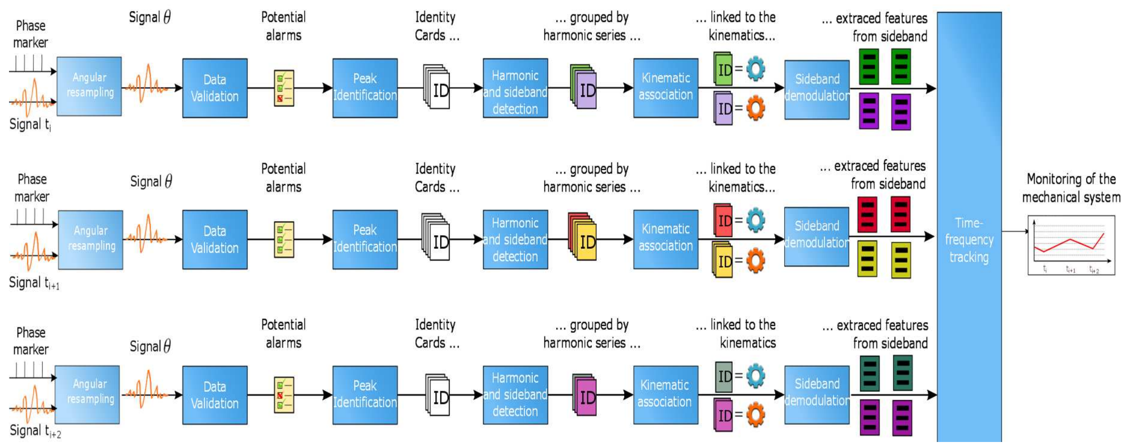

Figure 3. Synopsis of AStrion modules

AStrion-smart is an offline smart interface for looking at the online results in real time. If necessary, AStrion-smart can also run all AStrion modules again or for other measured data.

Further details on AStrion can be found in [2, 3, 9, 13, 14, 15, 16].

4.3 SMESA

The processing proposed in SMESA aims to detect both mechanical and electrical faults from electrical measures only. A simple analytical model from the three-phase current and/or voltage measured data provides a three-phase analytical signal around their fundamental frequency. Then a Lyon transform[19], called sometimes a Fortescue transform, will estimate instantaneous symmetrical components which reveal interesting properties such as the amount of electrical unbalance in the analysed system and the instantaneous three-phase electrical powers. Specific indicators are then output by SMESA. The strong interest of this module is its ability to detect not only electrical faults but also mechanical ones which have induced torque variations able to propagate through the mechanical system.

As for AStrion, an offline interface referred to as SMESA-smart allows a display of online results and a possible run on other data.

Further details on SMESA can be found in [4, 10, 11, 12].

5. Experimentations, tests and validation

During KAStrion project, the core idea was to validate AStrion and SMESA for the surveillance of the rotating machines in the nacelle of a wind turbine. First, a testbench has been designed as a wind turbine at a smaller scale and a maximum power of 10 kW.

A geared motor simulates the rotation of the blades of the turbine at a low speed. A multiplier with a transmission ratio of 100:1 delivers power to the output high-speed shaft and to a generator which can act as a brake and thereby generates the torque applied to the output shaft.

A strong interest of this testbench was the integration of load units on the main bearing, the planetary gear box and the output bearing. Load can be applied on the bearing of the main shaft by two hydraulic actuators in the axial and radial directions in order to simulate the weight of the hub, the blades, and the drag forces. The output bearing can be loaded radially by an actuator. Therefore, defects were generated within an endurance test program which allows the creation of a rich data base (~ 2 TB).

This testbench shown in Figure 4 was designed and installed by CETIM partner who has also expertised the failed components after dismantling in order to provide pictures and size of the defects.

Figure 4. Wind turbine test bench designed and installed in KAStrion project

The KAStrion CMS system and the required sensors have been installed for test and comparison with standard condition monitoring features. The main value of this validation was the presence of expertised faults in the data base due to the load units. In addition, different way of processing have been compared due to the presence of experts in the KAStrion consortium: CETIM and MECAL have analysed this data base and their results have been compared to KAStrion ones. The processing proposed by AStrion and SMESA was able to detect and characterize the nature and severity of the failures.

Further details can be found in [1, 2, 3, 4].

6. Onsite installation in Arfons windfarm

The final objective was then to test the KAStrion CMS system on onshore wind turbines. For this purpose, by courtesy of VALOREM, KAStrion system and the required sensors were installed in two wind turbines of 2 MW in Arfons wind farm in France by VALEMO and EC-System partners. See Figure 5 and Figure 6.

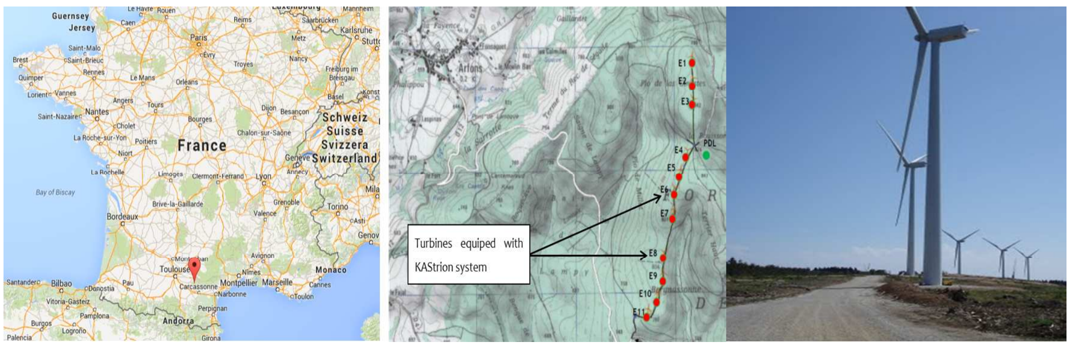

Figure 5. Arfons localization– Arfons site

Figure 6. From left to right: KAStrion system embedded in the nacelle of the wind turbine; Vibration sensor mounted on the housing of a gearbox; Current sensors; Voltage sensors in the measurement cabinet installation

Due to highly changing working consitions, and before the data validation, the KAStrion system will consider only data corresponding to specific operational states thanks to an original state setting proposed by EC-System partner. Further details could be found in [5].

Then the continuous acquired data and the results of the embedded processing, in particular AStrion and SMESA, are transmitted to the offline center. The tracking of the features shows no failure until now.

7. Conclusions

This paper has described the main contributions of KAStrion project which has proposed a new concept for the data processing. Interesting results have been obtained for the monitoring of the rotating parts on a specific test bench and in the nacelle of two onshore wind turbine. Vibration, current and voltage measurements were able to detect mechanical failures. KAStrion system is now ready for the go-to-market. It could be used in offshore windturbines without any adaptation. All the new processing proposed can also be applied in other complex systems[18].

Further details and results can be found in [1, 2, 3, 4, 5, 9, 10, 11, 12, 13, 14, 15, 16].

Perspectives would be to develop new trends for the surveillance of the tower, blades and foundation in order to be able to propose a complete solution for the monitoring of a wind turbine. Future works will be based on the same concept as in AStrion: no *a priori* information, advanced signal processing without setting, a reduce false alarm rate and a complete final description of the failures, including their degrees of severity.

Acknowledgements

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